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Multi-Beam Optical Tweezers

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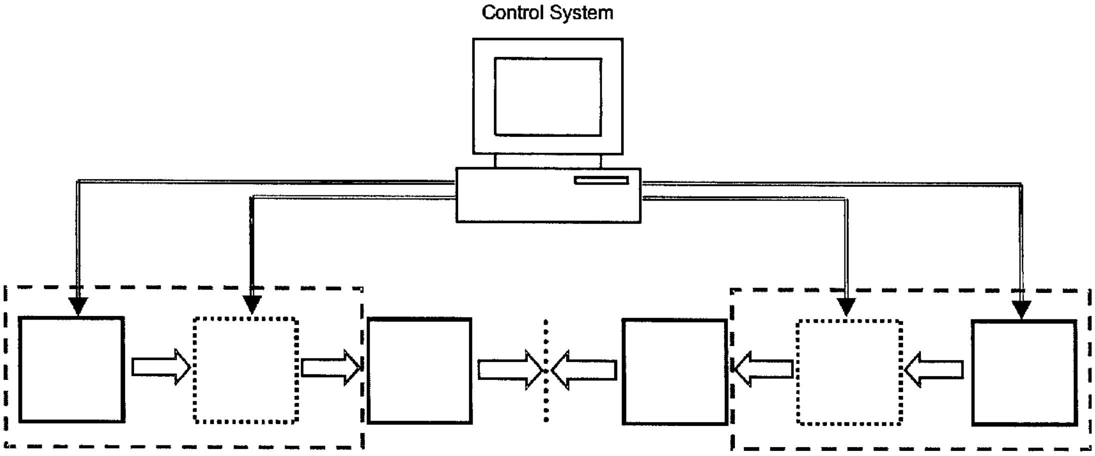

(57) Abstract: A set of multi-beam electromagnetic tweezers is provided comprising a multi-beam generator for emission of a plurality of electromagnetic beams, at least some of the electromagnetic beams intersecting each other, or, having an individually controlled polarization whereby the position and/or angular orientation of a plurality of micro-objects may be individually controlled.

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MULTIBEAM OPTICAL TWEEZERS

The present invention relates to manipulation of micro-objects, such as micro-components, biological cells, etc, using electromagnetic gradient forces.

It is well-known that in a strongly focused laser beam having an approximately Gaussian intensity profile, radiation pressure scattering and gradient force components are combined to give a point of stable equilibrium located close to the focus of the laser beam. Scattering force is proportional to optical intensity and acts in the direction of the incident laser light. Gradient force is proportional to the optical intensity and points in the direction of the intensity gradient.

This effect is utilized in a so-called optical tweezer or optical trap since the optical gradient forces in a focused light beam trap a small micro-object at the focal point of the light beam. The micro-object is typically immersed in a fluid medium whose refractive index is smaller than that of the micro-object. The optical tweezer technique has been generalized to enable manipulation of reflecting, absorbing and low dielectric constant micro-objects. Typically, a Gaussian beam is used for trapping of micro-object with a refractive index that is higher than the refractive index of its surroundings while a donut beam is used for trapping of a micro-object with refractive index that is lower than the refractive index of its surroundings.

In US 4,893,886, an optical trap for biological micro-objects is disclosed wherein biological micro-objects are kept in a single-beam gradient force trap using an infrared laser.

In US 6,055,106, an apparatus for manipulating micro-objects is disclosed that comprises a diffractive optical element for receiving a light beam and forming a plurality of separate light beams, each of which is focused to form a separate optical trap or tweezer.

Further, it is well-known to control the angular orientation of a micro-object with an optical tweezer. Mechanical detection and measurement of the angular momentum of light was first performed by Richard A. Beth, Physical Review, Volume 50, July 15, 1936. In US 6,180,940 B1, a method is disclosed of rotating micro-sized objects by directing a light beam with angular momentum towards a transparent anisotropic object in a suspension or solution.

An apparatus or a method for simultaneous and individual control of the position and angular orientation of a plurality of micro-objects is not disclosed in the prior art.

It is an object of the present invention to provide an apparatus and a method for individual control of the position and/or angular orientation of a plurality of micro-objects.

According to the present invention, the above-mentioned and other objects are fulfilled by a set of multi-beam electromagnetic tweezers comprising a multi-beam generator selected from the group consisting of

a) a multi-beam generator for emission of a plurality of electromagnetic beams, at least one of the electromagnetic beams having an individually controlled polarization; and

b) a multi-beam generator for emission of a plurality of electromagnetic beams with at least two intersecting or oppositely directed electromagnetic beams.

The basic principles of the present invention applies in general to beams of any kind of radiated energy, such as electromagnetic radiation, such as visible light, infrared radiation, ultraviolet radiation, X-rays, radio waves, etc, acoustic radiation, such as ultrasound radiation, etc, etc. The electromagnetic radiation may be spatially and/or temporally coherent, e.g. laser light or maser radiation.

It is an important advantage of the present invention that a plurality of electromagnetic beams, such as visible light beams, infrared light beams, ultraviolet light beams, etc, are provided so that the position of a plurality of micro-objects may be controlled individually.

It is a further advantage of the present invention that two or more beams may intersect each other at selected intersecting angles for further improvement of the trapping of a micro-object. For example, when a micro-object is trapped at the intersection of a plurality of beams, the focusing requirements of the individual beams are relaxed. Further, the direction of the trapping forces, such as the electromagnetic field gradient, at the intersection may be controlled by selective control of the field strength of the individual electromagnetic beams whereby the angular orientation of a trapped micro-object may be controlled.

Preferably, the at least two intersecting or oppositely directed electromagnetic beams are mutually incoherent. Hereby, formation of fringes by beam superposition is avoided.

In order to create a trapping force in a direction opposite the direction of propagation of a single beam, the single beam has to be extremely focused. This requirement is overcome in an embodiment of the present invention having mutually incoherent two beams intersecting each other at a 180° intersection angle, i.e. they are propagating along substantially the same axis of propagation but in opposite directions with focal points at substantially the same position thereby forming a significant trapping force along the propagation axis of the beams for trapping of a micro-object at the focal point of the beams.

Further, at least one of the beams may provide controlled angular momentum to a micro-object.

For example, a linearly polarized laser beam may be used to angularly align an optically trapped birefringent object as disclosed in E. Higurashi, R. Sawada, and T. Ito: "Optically induced angular alignment of trapped birefringent micro-objects by linearly polarized light", The American Physical Society, Vol. 59, No. 3, March 1999. When a transparent birefringent micro-object is trapped at the focal point of a linear polarized laser beam, the transmitted light generally becomes elliptically polarized light, i.e. the transmitted light has obtained angular momentum. As a result of the conservation of angular momentum, the object gains angular momentum in the opposite direction of the elliptically polarized light, and the object will rotate until either its slow axis or its fast axis (determined by the retardation of the object) becomes coincident with the vibration plane of the electric field. At this angular orientation the birefringent object no longer changes the state of polarization of the linear polarized incident light and is no longer subjected to a torque.

Angular alignment of micro-objects may be utilized for the assembly of micro-components for fabrication of three-dimensional structures or for alignment of micro-optical components in micro-opto-mechanical systems, or, in micro-fluid systems, e.g. for pumps and valves.

In another example, an elliptically polarized laser beam, preferably a circularly polarized laser beam, may be used to cause continuous rotation of a trapped transparent birefringent micro-object due to the transfer of the angular momentum of the beam. The rotation rate is proportional to the laser power and also depends on the degree of ellipticity. This may e.g. be utilized in micro-motors for micro-mechanical systems.

It should be noted that controlling the rotation rate by adjustment of the field strength of the trapping beam also affects the trapping force. This may be overcome according to the present invention by trapping a micro-object with intersecting beams individually transferring angular momentum to the micro-object. For example, when a micro-object is trapped by two oppositely directed beams of e.g. similar circular polarizations, these beams will transfer angular momentum of opposite directions to the trapped micro-object. Thus, a low rotation rate may be obtained with approximately the same field strength of the two beams thereby maintaining a large trapping force.

The multi-beam generator may comprise a beam emitter system for emission of the plurality of beams.

In a preferred embodiment of the invention, the multi-beam generator comprises an array of vertical cavity surface emitting lasers, VCSELs. An array of VCSELs is an attractive source of a plurality of substantially circular laser beams. The array may be one-dimensional or two-dimensional and the generated beams are Gaussian shaped with a low divergence and a low relative intensity noise due to the absence of mode competition and thus, the beams may be focused to very small spot sizes. Polarization may be controlled by asymmetric current injection.

The array of VCSELs may comprise integrated sub-wavelength transmission gratings SWTGs for enhancement of the VCSELs polarization properties. Preferably, the SWTGs is manufactured with nano-imprint lithography that offers a low cost, high throughput, reliable means to fabricate SWTGs. SWTGs are gratings with a period less than the wavelength of light and no non-zero order diffraction.

In an embodiment of the present invention comprising an array of VCSELs, controlled movement of a trapped micro-object may be obtained by controlled turning on and off of neighboring VCSEL emitters. For sufficiently closely propagating beams, a trapped micro-object will move to a neighboring beam upon turn-off of the presently trapping beam and turn-on of the neighboring beam, since the new trapping force will pull the micro-object to the turned-on beam. By appropriate sequential turn-on and turn-off of beams, the micro-object may be moved as desired. The path for an individual object or particle may be determined based on examination by another system, e.g. based on visual inspection, fluorescence, etc, e.g. for cytometry.

The multi-beam generator may further comprise a polarization control unit for individual control of the polarization of specific beams of the plurality of beams.

For example, polymers and liquid crystals may be used for polarization control.

The polarization control unit may comprise a first liquid crystal spatial light modulator LC-SLM for generation of elliptically polarized light from incident linearly polarized light. A polarizer may be positioned in front of the LC-SLM for generation of the linearly polarized light from incoming light with an arbitrary polarization.

Liquid crystal retarders are electrically variable wave plates. Retardance is altered by applying a variable, low voltage waveform. These retarders are made by placing a thin liquid crystal layer between parallel windows spaced a few microns apart.

The polarization control unit may further comprise a second LC-SLM positioned behind the first LC-SLM for rotation of the major axis of the elliptical polarization state. In a preferred embodiment of the invention, this is obtained by provision of a first quarter wave plate positioned between the first and the second LC-SLMs, and a second quarter wave plate positioned behind the second LC-SLM.

In another embodiment, the polarization control unit comprises three LC-SLMs for transformation of any input state of polarization of light into an arbitrary output state. For example, in Z. Zhuang, S. Suh, J.S. Patel, “Polarization controller using nematic liquid crystals”, Optics Letters 24 (10), 1999, an arbitrary polarization control unit for a single beam formed by three homogeneous nematic liquid-crystal cells is disclosed, which transforms any input state of polarization of light into an arbitrary output state, i.e. covering the entire Poincaré sphere.

The beam emitter system may comprise a light source for emission of an electromagnetic beam, such as a visible light beam, an infrared light beam, an ultraviolet light beam, etc, and a beam forming means for dividing the source beam into the plurality of beams, or, for deflecting the beam. The electromagnetic beam may be spatially and/or temporally coherent.

The beam forming means may comprise a phase contrast imaging system for receiving the electromagnetic beam and forming the plurality of electromagnetic beams. An advantageous phase contrast imaging system is disclosed in WO96/34307.

The beam forming means may comprise deflecting means for deflecting the plurality of beams into desired directions of propagation. The deflection of individual beams may be dynamically controlled facilitating controlled movement of trapped particles. The deflection may be based on reflection, refraction, absorption, diffraction, scattering, etc, of the electromagnetic beam.

For example, the beam forming means may comprise a diffractive element , such as a diffractive optical element, etc, for receiving the electromagnetic beam and forming the plurality of electromagnetic beams. Preferably, the diffractive element has a separate grating for each beam to be generated. It is also preferred to use gratings without a zero order diffraction beam, such as blazed gratings. The gratings may be dynamically adjustable. Each of the deflection gratings may be a combination of an amplitude and phase grating, however, phase only gratings are presently preferred due to their low energy loss. Different gratings may occupy a common area of the diffractive element, i.e. the gratings may be frequency multiplexed, and/or, different gratings may occupy separate areas of the diffractive element, i.e. the gratings may be tiled, e.g. checkerboard tiled or pie tiled.

Alternatively, the deflecting means may comprise an array of adjustable refractive prisms. The deflection of an individual prism may be controlled, e.g., by mechanical forces acting on the prism, or, by controlling the refractive index profile.

In yet another embodiment of the invention, the deflecting means comprise an array of adjustable mirrors, such as an array of micro-mirrors, such as a Micro-Opto-Electro-Mechanical System (MOEMS), a membrane with a plurality of mirror actuators, etc.

In still another embodiment of the invention, the deflecting means is adapted to sequentially deflect a single beam into the desired directions of propagation thereby forming the plurality of beams. Preferably, the beam is turned off between desired tweezer or trapping positions and turned on at the desired positions. The deflecting means may comprise two mirrors whose axes of rotation are perpendicular to each other facilitating scanning of the beam across a desired area, e.g. line by line like a TV scan. The polarization control unit may operate on the beam before the deflecting means, or, the polarization control unit may be scanned by the deflecting means.

The multi-beam generator may further comprise focusing means for individually focusing beams of the plurality of beams. The focusing may be based on reflection, refraction, absorption, diffraction, scattering, etc, of the electromagnetic beam.

The focusing means may comprise an array of adjustable focusing gratings where each of the focusing gratings may be a combination of an amplitude and phase grating, however, phase only gratings are presently preferred due to its low energy loss. In a preferred embodiment, the focusing means comprise Fresnel zone plates.

Alternatively, the focusing means comprise an array of adjustable refractive lenslets. The focusing of individual lenslets may be controlled by, e.g., mechanical forces acting on the lenslet, or, by controlling the refractive index profile.

In yet another embodiment of the invention, the focusing means comprise an array of adjustable curved mirrors, such as an array of micro-mirrors, e.g. MOEMS, a membrane with a plurality of mirror actuators, etc.

In the field of diffractive optical element it is well-known that it is possible to integrate several diffraction gratings in one diffractive optical element, thereby integrating several optical functions, such as lenses, beam splitters, etc. in one optical component. Likewise, the focusing means and the deflecting means may be physically integrated, e.g., by combining adjustable diffractive deflection grating with static refractive lenslets.

This possibility of integrating several optical functions in one diffractive element and the possible use of semiconductor lasers, such as an array of semiconductor lasers, such as VCSELs, etc, reduce the size of the tweezers according to the present invention considerably since the use of bulky classical optical components such as lenses, beam splitters, etc. and bulky gas lasers with their bulky power supplies are avoided. This also means that use of components sensitive to ambient conditions are avoided, thereby creating hitherto unseen compact and robust tweezers.

Furthermore, the possibility of integrating several optical functions in one diffractive element makes it possible to implement optical functions which can not be implemented with classical optical components since the physical size of these components restricts the possibilities of positioning of the components, e.g. for creation of two narrowly spaced parallel light beams.

In Wanji Yu et. al.: "Polarization-multiplexed diffractive optical elements fabricated by sub-wavelength structures", Applied optics, Vol. 41, No. 1, 1 January 2002, polarization multiplexed phase-only diffractive optical elements with sub-wavelength structures are proposed and fabricated. The differences between the phase modulations result from the differences between the effective indices exhibited in the sub-wavelength structures with various filling factors and surface profiles, and the phase retardations are obtained by the relief depth of the structures.

Preferably the size of the polarization control unit is minimized by assembling its individual components into a sandwich construction.

For further size reduction, the deflecting means and the focusing means may be integrated into the sandwich construction, and in an embodiment with an array of semiconductor light sources, such as VCSEL light sources, the array may also be integrated into the sandwich construction.

For a better understanding of the present invention reference will now be made, by way of example, to the accompanying drawings, in which:

Fig. 1 schematically illustrates a set of multi-beam optical tweezers according to the invention,

Fig. 2 schematically illustrates another multi-beam optical tweezer according to the invention,

Fig. 3 schematically illustrates the operation of a polarization control unit according to the invention,

Fig. 4 schematically illustrates a multi-beam generator with blazed gratings,

Fig. 5 schematically illustrates a polarization control unit according to the invention,

Fig. 6 illustrates another polarization control unit according to the invention,

Fig. 7 illustrates state of polarization mapping on a Poincaré sphere,

Fig. 8 is a graphical representation of output polarization states of the polarization control unit of Fig. 5,

Fig. 9 shows an experimental system for determination of output polarizations of the polarization control unit of Fig. 5,

Fig. 10 illustrates a set of measurements performed with the system of Fig. 9,

Fig. 11 illustrates another set of measurements performed with the system of Fig. 9,

Fig. 12 illustrates still another set of measurements performed with the system of Fig. 9,

Fig. 13 is a plot of the normalized intensity as a function of the analyzer rotation angle determined with the system of Fig. 9, and

Fig. 14 is a plot of the normalized intensity as a function of the analyzer rotation angle for elliptically polarized light with different angular positions of the major axis as determined with the system of Fig. 9.

It should be noted that although arrays of light sources, the deflecting means, the polarization control unit in the present figures are depicted as planar members for clarity, it may be preferred that such arrays form a curved surface, such as a spherical surface.

Fig. 1 shows a blocked schematic of a set of multi-beam optical tweezers 10 according to the present invention, comprising two multi-beam generators 12, 13 for generation of a plurality of beams. Provision of two multi-beam generators 12, 13 facilitates generation of intersecting beams, such as beams with overlapping focus regions and propagating in opposite directions providing trapping of a micro-object in the overlapping focus region. The generators 12, 13 may comprise a multiple beam light source with built-in polarization control, such as VCSELs with asymmetric current control and/or sub-wavelength gratings, such as switchable sub-wavelength gratings.

Alternatively, the multi-beam generator 12, 13 may comprise a beam emitter system 14, 15 comprising a light source for emission of an electromagnetic beam. A beam forming means, such as a diffractive element, e.g. with blazed gratings, a phase contrast imaging system, etc, may receive the electromagnetic beam and form the plurality of electromagnetic beams.

The multi-beam generator 12, 13 may further comprise a polarization control unit 16, 17 for individual control of the polarization of specific beams of the plurality of beams.

The basic capabilities of a polarization control unit 16, 17 according to the present invention is illustrated in Fig. 3 indicating that an arbitrary input polarization state may be converted into any arbitrary output polarization state.

The focusing optics 18, 19 may comprise a microscope objective and one or more beam scaling lenses for imaging the plurality of beams onto the trapping region 22 where the beams are focused for trapping micro-objects.

Fig. 2 shows a blocked schematic of another set of multi-beam optical tweezers 10 according to the present invention corresponding to the left half of Fig. 1, comprising a multi-beam generator 12 for generation of a plurality of beams, at least some of the beams having an individually controlled polarization. As in Fig. 1, the generator 12 may comprise a multiple beam light source with built-in polarization control, such as VCSELs with asymmetric current control and/or sub-wavelength gratings, such as switchable sub-wavelength gratings.

Fig. 4 shows an exploded view of a sandwich construction of a multi-beam generator 12 and a polarization control unit 16 for formation of four beams with individual polarizations. The multi-beam generator 12 comprises beam deflecting means 14 with adjustable blazed gratings 28 for individual deflection of the four beams, and beam focusing means 24 with lenslets 26.

In the present figures, the beam forming means, the beam deflecting means, the beam focusing means, and the polarization control unit are shown as plane members. However, the members may be curved if appropriate, e.g. for beam forming.

Fig. 6 shows an embodiment of the polarization control unit 16, comprising three LC-SLMs 28, 30, 32 for transformation of any input state of polarization of light into an arbitrary output state. The slow axes 34, 36, 38 are indicated in the Figure. The first and third LC-SLM 28, 32 are aligned and the middle LC-SLM 30 is turned 45° in relation to the other two LC-SLMs 28, 32. A series of linear birefringent elements (such as a homogeneous nematic liquid-crystal slab in our case) are described by a series of rotations on the Poincaré sphere with respect to axes that lie on the equatorial plane as indicated in Fig. 7. In Fig. 7, the three LC-SLM 28, 30, 32 correspond to three axis LR, HV, and PQ, respectively. By changing the applied voltages, the amount of rotation is controlled with respect to each axis to achieve the transformation from one arbitrary polarization to another arbitrary polarization. For further explanation of the Poincaré Sphere, reference is made to R.M.A. Azzam, N.M. Bashara: "Ellipsometry and Polarized Light", Elsevier, Amsterdam, 1977.

It is also possible to generate an arbitrary state of polarization from linearly polarized light combining two LC-SLMs and two quarter wave plates, as shown in Fig. 5. The input light is incident on a first LC-SLM (SLM-1) which in combination with the linear polarizer converts the input light to elliptically polarized light. The second SLM, SLM-2, is placed between two crossed quarter wave plates ($\lambda/4$) for rotation of the major axis of the elliptically polarized light generated by SLM-1. In this set-up, the major axes of the two SLMs are rotated 45° counter clockwise in relation to the axis of the polarizer.

Thus, the system comprises two subsystems. The first subsystem consists of the linear polarizer and SLM-1 generating elliptically polarized light from any arbitrary input polarization state (the elliptical generator). The second subsystem consists of SLM-2 and two quarter wave plates for rotation of the major axis of the elliptical polarization state (the elliptical rotator). The resulting output vector of the system is calculated as a matrix multiplication of the two subsystem Jones matrices (T1 and T2) with the input vector. This system configuration can accept any state of input polarization, with the only restriction being, that there should be a polarization component of the input light in the polarization direction of the input polarizer.

A graphical representation of the different states of polarization obtainable with this 2D polarization encoding system is given in Fig. 8. The phase modulation of SLM-1 and SLM-2 are the parameters which determine the type and direction of the output polarization which is shown graphically. The direction of the elliptically polarized light changes from left handed to right handed when the phase modulation of SLM-1 is above π. As seen from this graphical table, any arbitrary state of elliptical polarization may be generated if both SLM-1 and SLM-2 can produce a phase modulation of at least 2π.

An experimental system has been implemented using a pair of parallel-aligned LC-SLM (PAL-SLM) supplied by Hamamatsu Photonics. The Hamamatsu X7665 PAL-SLM is a phase-only LC-SLM. It has a parallel aligned rather than twisted nematic liquid crystal element. It is a non-pixelated optically addressed SLM, with VGA (640 * 480 pixel) addressing resolution. The active phase modulation area of the PAL-SLMs is 20 * 20 mm^2 with a spatial resolution of approximately 50 lp/mm.

A schematic diagram of the experimental system is shown in Fig. 9. The laser is a linearly polarized 30 mW He-Ne which is used with a beam expander and a spatial filtering element to produce a plane polarized wave. To ensure that the linearly polarized light is aligned to the y-direction of the system, a linear polarizer (Pol-1) oriented 45° to the fast axis of both PAL-SLMs is placed after the beam expander. The PAL-SLM is a reflection geometry SLM so beam splitting cubes have been used to separate input and output light. The wave front reflected from SLM-1 is imaged onto SLM-2 with a 4-f set-up (lenses L1 and L2) through beam splitter (BS-2).

The encoded wave front reflected from SLM-2 is imaged simultaneously onto a CCD camera and a photo detector through a third lens (L3) and a beam splitter (BS-3). A quarter wave plate (λ/4) is placed between the SLMs and a second one, is placed between SLM-2 and lens L3. The encoded information is analyzed by means of a Glan-Thomson polarizer (Pol-2) placed after lens L3. In this set-up SLM-1 and Pol-1 convert the polarized input light into elliptically polarized light and SLM-2 together with the two crossed quarter wave plates, rotates the major axis of the elliptically polarized light. The two SLMs have been calibrated, so a known grey level in the optical addressing system corresponds to a known phase shift in the SLM. The PAL-SLM is capable of generating a maximum phase shift of 3π at 633 nm. This phase shift is controlled by the 8-bit grayscale (256 grey values) of the optical addressing LCD corresponding to a resolution of around 3-4° per grayscale value. This limitation in the precision of grayscale addressing is due to an inherent non-linear response for the grayscale addressing to phase modulation.

A lock-in amplifier and photodiode (D) have been used to make quantitative measurements of the intensity and a high resolution CCD camera was used to record the experimental images.

Two different types of experiments have been carried out to characterize the 2D encoding system. One, qualitative, in which the different states of polarized light are visualized by means of a polarizer and a CCD camera and another, quantitative, in which photo detector measurements show the system is capable of accurately rotating elliptically polarized light by a specified angle.

For demonstration purposes, the PAL-SLMs are divided into four quadrants for formation of four tweezer beams, each of which has an individually adjustable level of phase retardation. In principle, the active area of the SLM could be subdivided into any number of arbitrary pixels limited only by the resolution of the device. The size of each test quadrant is approximately 2 * 2 mm^2 with the effective addressing area limited by an aperture placed in front of one of the SLMs.

Different test patterns have been generated to illustrate that the system can produce different states of polarization in the four arbitrary retardation areas. Fig. 10 shows the graphical representations of the polarization state and rotation introduced by each SLM and the polarization encoded output from the system. The upper part of Fig. 10(a) shows the test patterns of SLM-1, SLM-2 and the resulting encoded information. Quadrants 1 and 3 of SLM-2 generate linearly polarized light along the x-direction of the system as indicated by horizontal arrows in Fig. 10(a), and the quadrants 2 and 4 generate linearly polarized light in the y-direction of the system. Quadrants 1 and 3 of SLM-2 introduce no phase retardation i.e. no rotation of the major axis, and quadrants 2 and 4 introduce a phase retardation of π corresponding to 90° rotation of the major axis. It should be noted that the angle of rotation introduced by SLM-2 is equal to half the phase retardation of the SLM. The outputs of all four quadrants have the same state of polarization, in this case linearly polarized light along the x-direction. The corresponding experimental results are shown in the lower part of Fig. 10(a). The polarization state is visualized by means of a linear polarizer oriented in the x-direction of the system, resulting in darkness for light polarized in the y direction and high brightness for light polarized in the x-direction. Fig. 10(b) shows that the system is able to generate the expected high contrast images between dark and bright corresponding to the desired state of polarization. In the image of the encoded state of polarization, all four quadrants are bright, corresponding to linearly polarized light in the x-direction. There is a slight inhomogeneity in the observed intensity pattern, this can primarily be attributed to variations in the quality of the expanded laser beam and some transmission of the pixelated addressing pattern through the PAL-SLMs.

Fig. 10(b) corresponds to Fig. 10(a), however the phase retardations of SLM-2 have been changed such that the resulting encoded state of polarization is vertically polarized light in all four quadrants.

In Fig. 11(a), the incoming light is circularly polarized. In this case, SLM-1 generates circularly polarized light in all four quadrants whereas SLM-2 only rotates the state of polarization 90° in quadrants 2 and 4. From the image of the encoded information, it can be seen that the brightness of each quadrant is nearly equal, indicating that the system has only rotated the circularly polarized light without significantly affecting the state of polarization. In the experimental results shown in Fig. 11(b) quadrants 1 and 3 of SLM-1 are encoded to produce circular polarized light whilst quadrants 2 and 4 generate orthogonal linearly polarized light. SLM-2 is addressed to rotate the state of polarization by 180°, 270°, 0° and 90° in quadrants 1-4 respectively. In the image of the resulting encoded information, it should be noted that the polarization state of the two quadrants with circularly polarized light is conserved as would be expected from the simple rotation of circularly polarized light by SLM-2. Referring to Fig. 11(b), it can be seen that the measured intensity for circular polarized light is approximately half that of the linearly polarized light. This is as expected for the case when the output polarizer is aligned to the direction of the linear polarized light in quadrants 2 or 4.

The results shown in Fig. 12(a) and (b) demonstrate the capability of the encoding system to simultaneously generate linearly, circularly and elliptically polarized light and at the same time rotate the major axes of the polarization state individually in the four quadrants. The regions in which elliptically polarized light is present can be distinguished by the different intensities from those regions having linearly and circularly polarized light.

Quantitative measurements describing the system performance are necessary to examine the precision and flexibility of elliptical rotation. For these experiments, SLM-1 is addressed with a grey value corresponding to a given phase modulation (state of elliptical polarized light), meanwhile SLM-2 is addressed with a phase modulation equal to a given rotation of the major axis. The resulting state of polarized light is detected by means of an analyzer (polarizer) and a photo detector as shown in Fig. 9.

In Fig. 13, the measured and calculated intensity is plotted for linearly, elliptically and circularly polarized light as a function of the rotation angle of the analyzer. It is shown that the system can generate linearly polarized light ($\phi_1(x_m,y_n)=0°$, $\phi_2(x_m,y_n)=0°$), elliptically polarized light ($\phi_1(x_m,y_n)=50°$, $\phi_2(x_m,y_n)=0°$, ellipticity $\eta = \cos(\phi_{1/2})/\sin(\phi_{1/2}) \approx 0.47$) and circularly polarized light ($\phi_1(x_m,y_n)=90°$, $\phi_2(x_m,y_n)=0°$). Referring to Fig. 13, it can be seen that there is small difference between the measured intensity and the expected intensity as a function of polarizer orientation. Probably, this difference is due to two separate artifacts of the experimental system. Firstly, there is a non-uniformity in the transmission of the polarizer as a function of the rotation angle. This is the primary cause of the difference between the theoretical and experimental results in the region from 90° to 270° in Fig. 13, as shown most clearly by the results for the linearly and elliptically polarized light. Secondly, there is a quantisation of the phase shift in the PAL-SLM, which arises from the limited number of available grey levels in the optical addressing LCD. This in turn limits the precision to which a desired phase shift can be produced. Thus in the case of the curve for the circularly polarized light, there remains a slight ellipticity in the polarization state which is responsible for the slight undulations seen in Fig. 13. Results showing the system performance with generation of elliptically polarized light, $\phi(x_m,y_n)=50°$, and the subsequent rotation of the major axis for four different rotation angles are shown in Fig. 14.

From Fig. 14, it is apparent that the encoding system is able to generate elliptically polarized light and independently rotate the major axis, without significantly changing the ellipticity. In this case, the ellipticity is fixed at $\eta \approx 0{,}47$ which determines the minima and the maxima of the intensity on a scale normalized to the intensity of linearly polarized light as shown in Fig. 13. The major axis of the ellipse is rotated from 0° to 180° which is seen as a displacement of the position of the minima and maxima with respect to the unrotated position (0°). This rotation is accomplished without an appreciable change in the amplitude of the detected intensity. It can also be seen that there is, as expected, very good agreement between elliptically polarized light rotated 0° and 180°. The small variation of the observed intensity is due to the experimental errors discussed previously.

CLAIMS

1. A set of multi-beam electromagnetic tweezers comprising a multi-beam generator selected from the group consisting of

   a) a multi-beam generator for emission of a plurality of electromagnetic beams, at least one of the electromagnetic beams having an individually controlled polarization; and

   b) a multi-beam generator for emission of a plurality of electromagnetic beams with at least two intersecting or oppositely directed electromagnetic beams.

2. A set of multi-beam electromagnetic tweezers according to claim 1, comprising a multi-beam generator for emission of a plurality of electromagnetic beams, at least one of the electromagnetic beams having an individually controlled polarization.

3. A set of multi-beam electromagnetic tweezers according to claim 1, comprising a multi-beam generator for emission of a plurality of electromagnetic beams with at least two intersecting or oppositely directed electromagnetic beams.

4. A set of multi-beam electromagnetic tweezers according to any of the preceding claims, wherein the multi-beam generator comprises an array of vertical cavity surface emitting lasers VCSELs.

5. A set of multi-beam electromagnetic tweezers according to claim 4, wherein the array of VCSELs comprises integrated sub-wavelength transmission gratings SWTGs.

6. A set of multi-beam electromagnetic tweezers according to claim 4 or 5, further comprising a polarization control unit for individual control of the polarization of specific beams of the plurality of beams.

7. A set of multi-beam electromagnetic tweezers according to any of claims 1-3, wherein the multi-beam generator comprises a beam emitter system for emission of the plurality of beams and a polarization control unit for individual control of the polarization of specific beams of the plurality of beams.

8. A set of multi-beam electromagnetic tweezers according to any of the preceding claims, wherein the multi-beam generator further comprises beam forming means for forming the plurality of beams.

9. A set of multi-beam electromagnetic tweezers according to claim 8, wherein the beam forming means comprises beam deflecting means for individually deflecting beams of the plurality of beams.

10. A set of multi-beam electromagnetic tweezers according to claim 9, wherein the beam deflecting means is adapted to sequentially deflect a single beam in a plurality of directions thereby forming the plurality of beams.

11. A set of multi-beam electromagnetic tweezers according to any of the preceding claims, wherein the multi-beam generator further comprises focusing means for individually focusing beams of the plurality of beams.

12. A set of multi-beam electromagnetic tweezers according to any of claims 6-11, wherein the polarization control unit comprises a first liquid crystal spatial light modulator LC-SLM.

13. A set of multi-beam electromagnetic tweezers according to claim 12, wherein the polarization control unit further comprises a polarizer positioned in front of the LC-SLM.

14. A set of multi-beam electromagnetic tweezers according to claim 13, wherein the polarization control unit further comprises a second LC-SLM positioned behind the first LC-SLM.

15. A set of multi-beam electromagnetic tweezers according to claim 14, wherein the polarization control unit further comprises a first quarter wave plate positioned between the first and the second LC-SLMs, and a second quarter wave plate positioned behind the second LC-SLM.

16. A set of multi-beam electromagnetic tweezers according to any of claims 6-15, wherein the polarization control unit forms a sandwich construction with its individual components substantially abutting neighboring components.

17. A set of multi-beam electromagnetic tweezers according to claim 16 as dependant on claim 6, wherein the VCSELs and the polarization control unit form a sandwich construction.

18. A set of multi-beam electromagnetic tweezers according to any of claims 6-17, wherein the polarization control unit comprises three LC-SLMs positioned one behind the other along a light propagation path for transformation of an arbitrary polarization of electromagnetic beam into another desired arbitrary polarization,

with the slow axes of the first and the last LC-SLM in parallel and the slow axes of the middle LC-SLM being rotated substantially 45° in relation to a corresponding slow axes of the other two LC-SLMs.

19. A set of multi-beam electromagnetic tweezers according to any of the preceding claims, wherein the beam emitter system comprises a light source for emission of an electromagnetic beam, and a diffractive element for receiving the electromagnetic beam and forming the plurality of electromagnetic beams.

20. A set of multi-beam electromagnetic tweezers according to claim 19, wherein the diffractive element comprises tiled gratings.

21. A set of multi-beam electromagnetic tweezers according to any of claims 1-18, wherein the beam emitter system comprises a light source for emission of an electromagnetic beam, and a phase contrast imaging system for receiving the electromagnetic beam and forming the plurality of electromagnetic beams.

22. A set of multi-beam electromagnetic tweezers according to any of claims 1-20, wherein the beam emitter system comprises a light source for emission of an electromagnetic beam, and a blazed grating for receiving the electromagnetic beam and forming the plurality of electromagnetic beams.

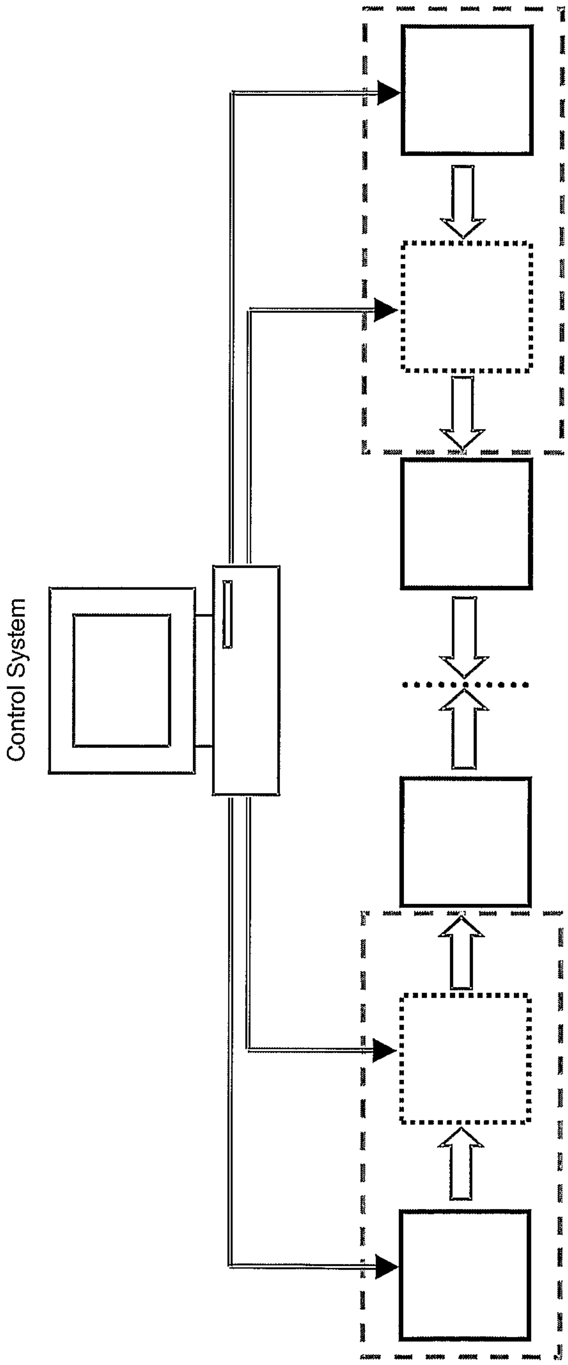


Fig. 1

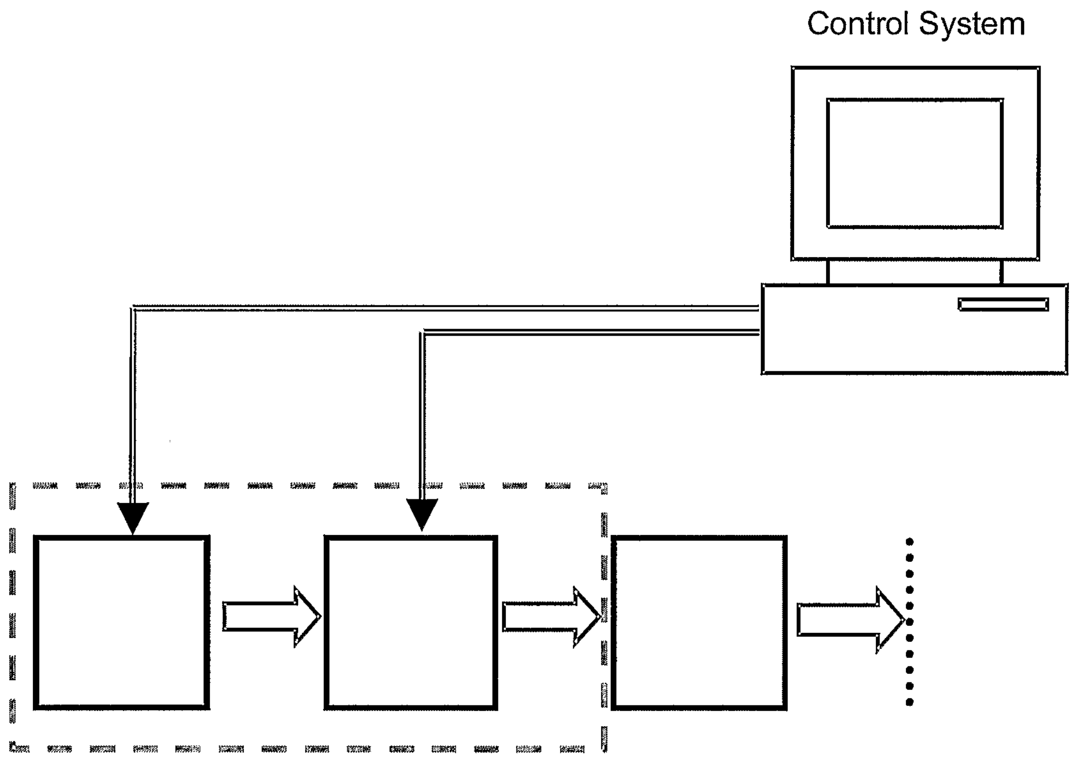


Fig. 2

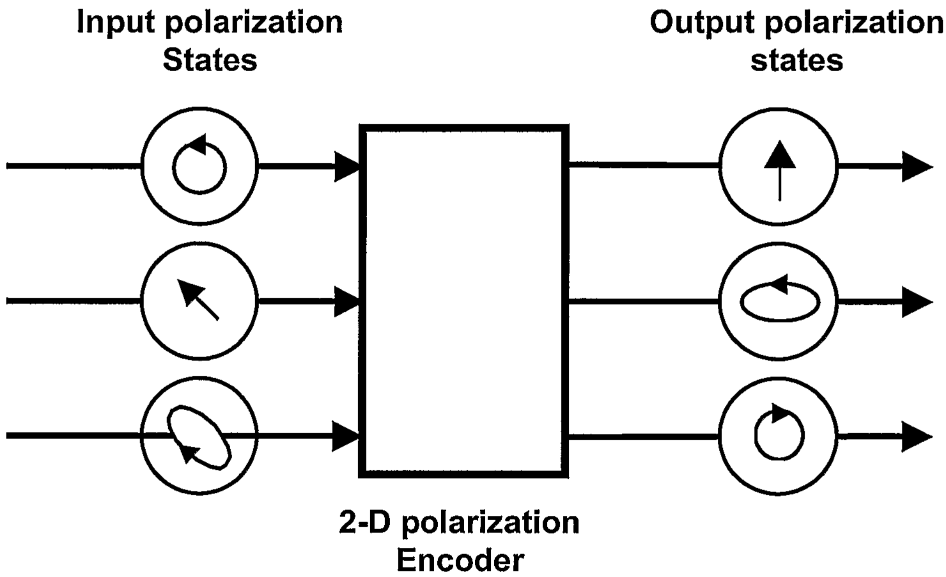

Input polarization
States
Output polarization
states
2-D polarization
Encoder

Fig. 3

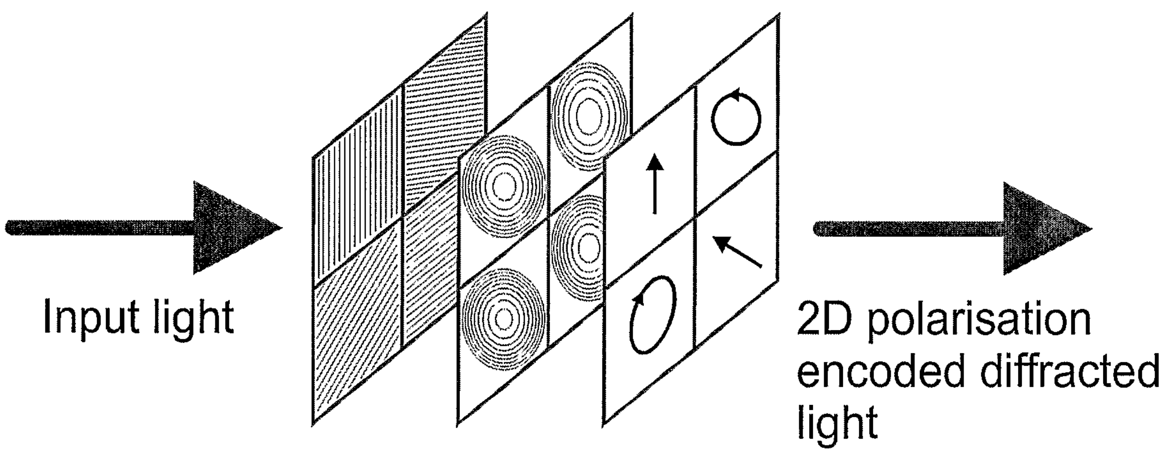

Input light
2D polarisation
encoded diffracted
light

Fig. 4

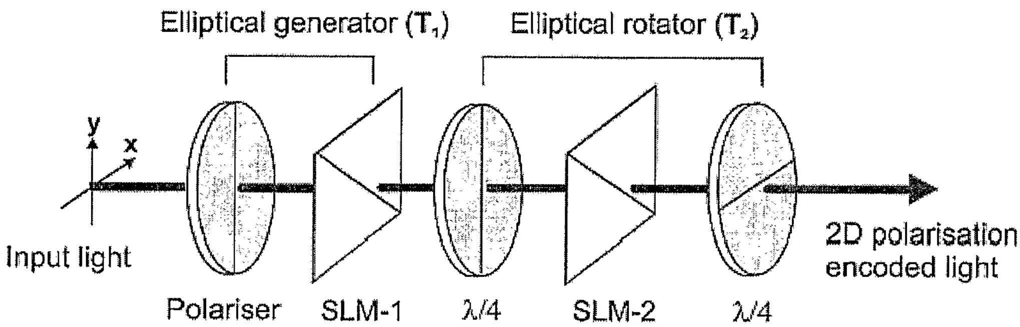


Fig. 5

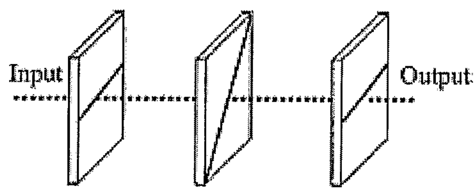


Fig. 6

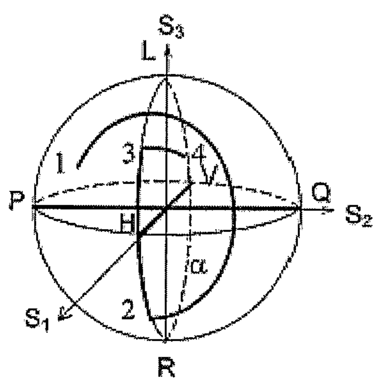


Fig. 7

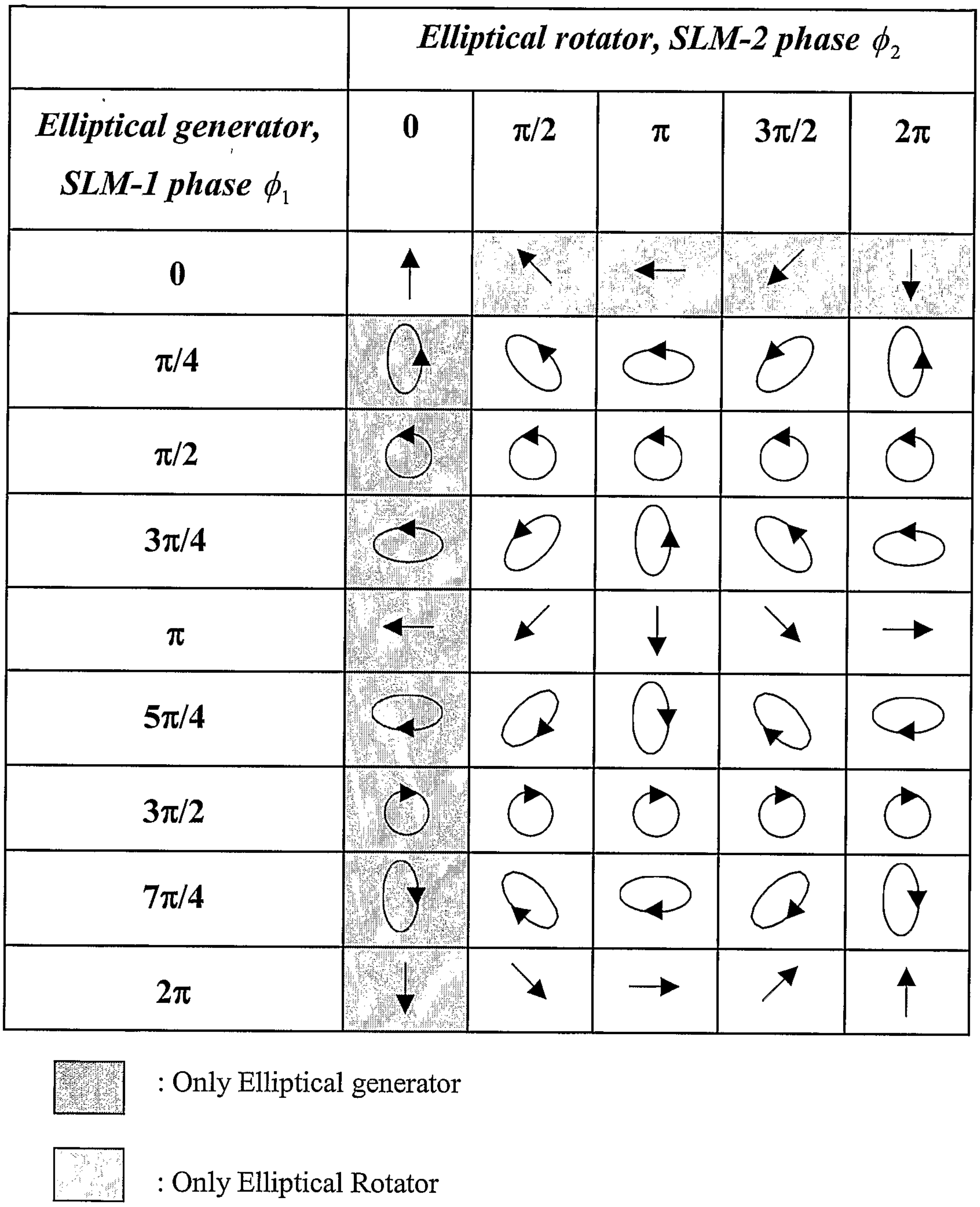

Elliptical rotator, SLM-2 phase ϕ_2
Elliptical generator, SLM-1 phase ϕ_1
0
π/2
π
3π/2
2π
0
π/4
π/2
3π/4
π
5π/4
3π/2
7π/4
2π
: Only Elliptical generator
: Only Elliptical Rotator

Fig. 8

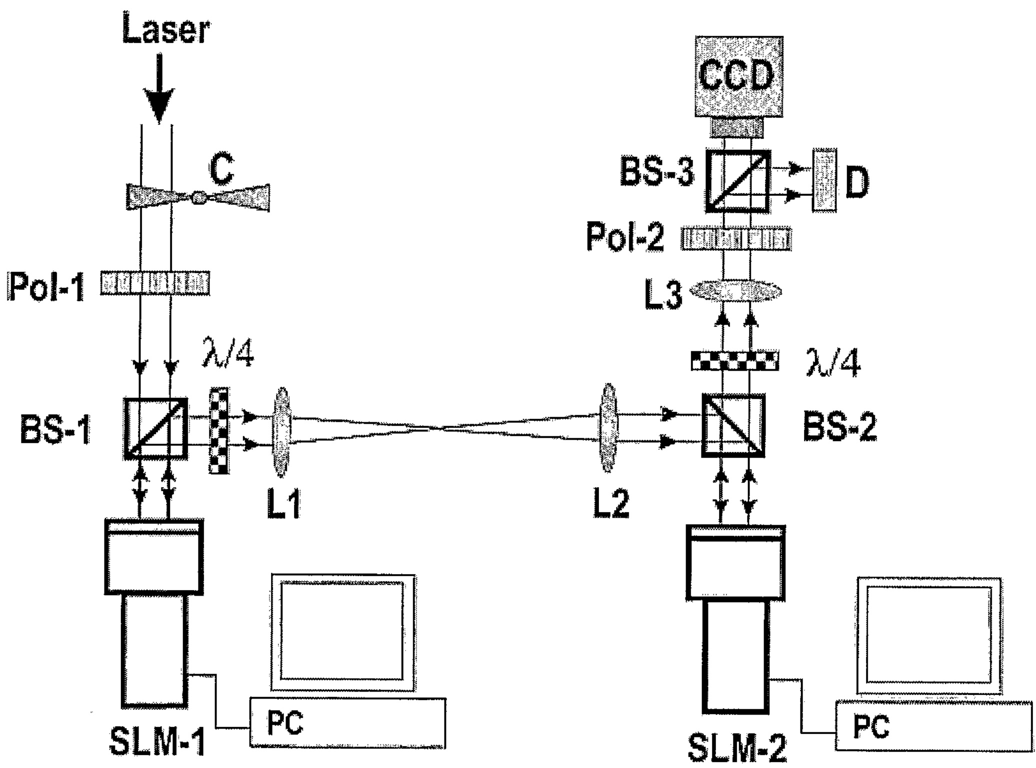

Laser
C
Pol-1
BS-1
$\lambda/4$
L1
L2
SLM-1
PC
CCD
BS-3
D
Pol-2
L3
$\lambda/4$
BS-2
SLM-2
PC

Fig. 9

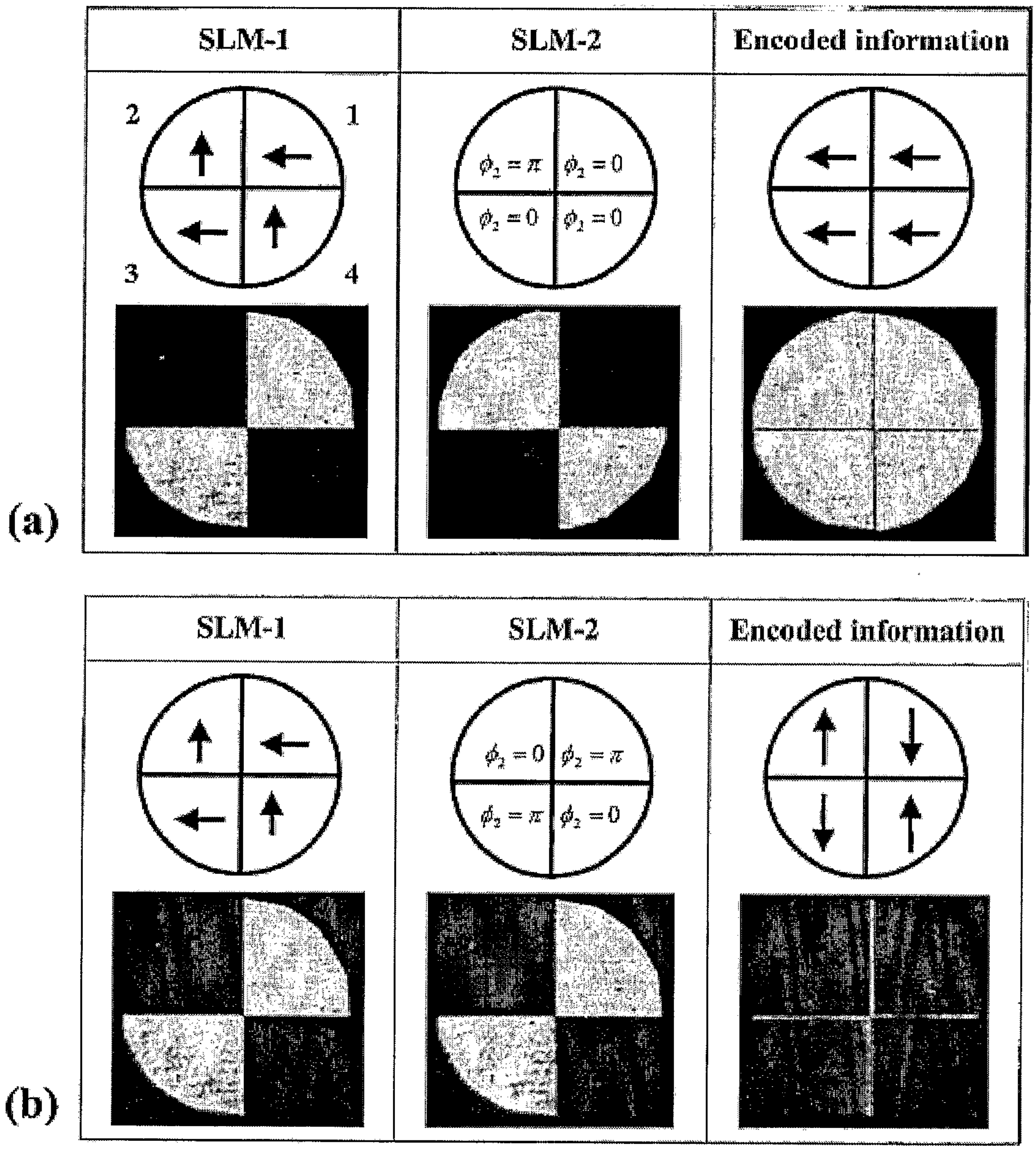

SLM-1
SLM-2
Encoded information
2
1
3
4
$\phi_2 = \pi$
$\phi_2 = 0$
$\phi_2 = 0$
$\phi_2 = 0$
(a)
SLM-1
SLM-2
Encoded information
$\phi_2 = 0$
$\phi_2 = \pi$
$\phi_2 = \pi$
$\phi_2 = 0$
(b)

Fig. 10

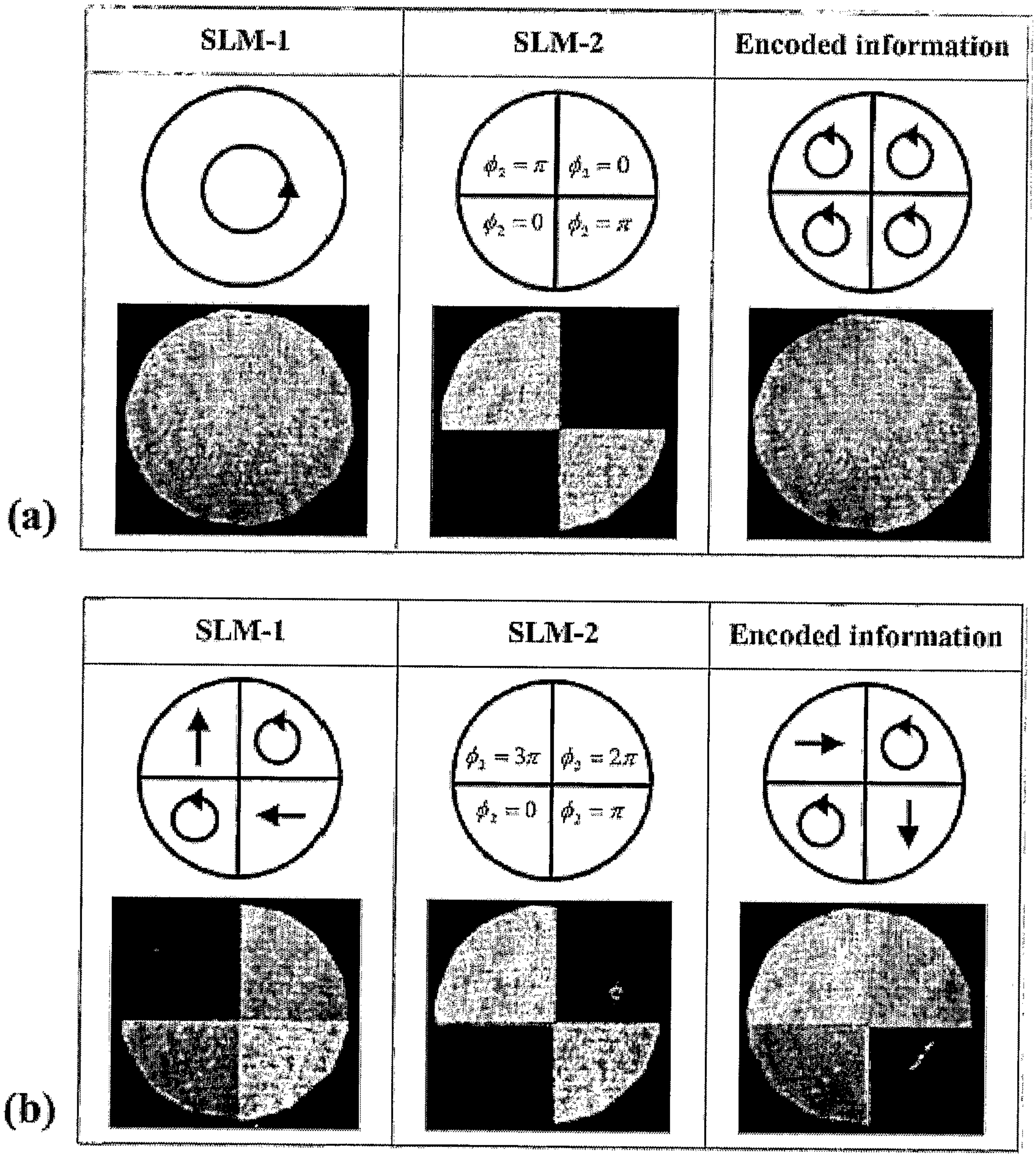
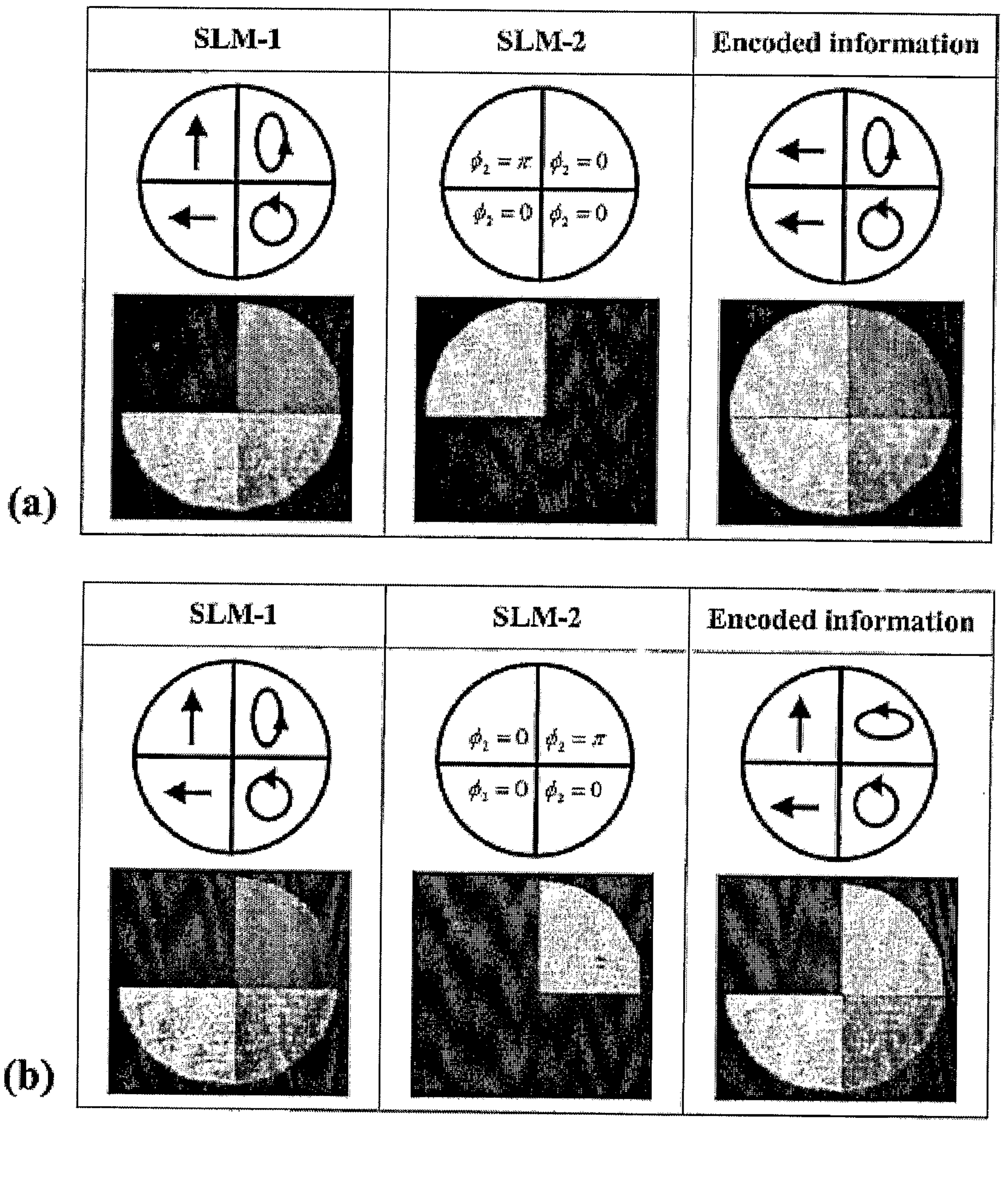

SLM-1
SLM-2
Encoded information
$\phi_2 = \pi$
$\phi_2 = 0$
$\phi_2 = 0$
$\phi_2 = \pi$
(a)
SLM-1
SLM-2
Encoded information
$\phi_2 = 3\pi$
$\phi_2 = 2\pi$
$\phi_2 = 0$
$\phi_2 = \pi$
(b)

Fig. 11



SLM-1
SLM-2
Encoded information
$\phi_2 = \pi$
$\phi_2 = 0$
$\phi_2 = 0$
$\phi_2 = 0$
(a)
SLM-1
SLM-2
Encoded information
$\phi_2 = 0$
$\phi_2 = \pi$
$\phi_1 = 0$
$\phi_2 = 0$
(b)

Fig. 12

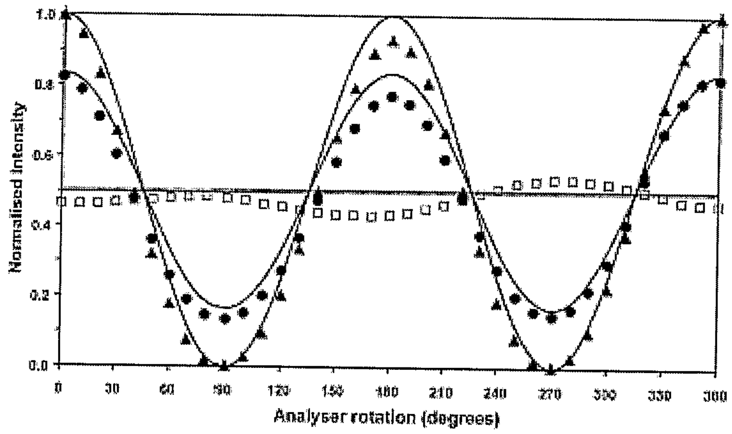

Normalised intensity
1.0
0.8
0.6
0.4
0.2
0.0
0
30
60
90
120
150
180
210
240
270
300
330
360
Analyser rotation (degrees)

Fig. 13

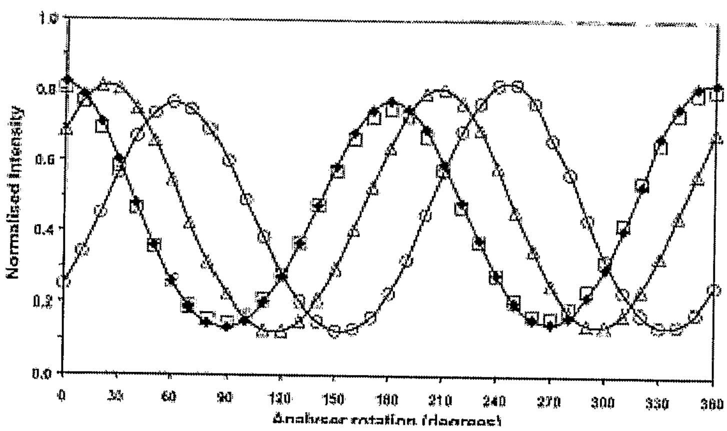

Normalised intensity
1.0
0.8
0.6
0.4
0.2
0.0
0
30
60
90
120
150
180
210
240
270
300
330
360

Fig. 14

INTERNATIONAL SEARCH REPORT

In tional Application No
PCT/DK 03/00049

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H05H3/04

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H05H G21K

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

INSPEC, EPO-Internal, WPI Data, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
P,A	US 2002/115164 A1 (WANG ET AL.) 22 August 2002 (2002-08-22) column 8, paragraph 112 - paragraph 113 ---	1,4,8
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A	KIM J A ET AL: "Cold atoms in a hollow mirror trap" INTERNATIONAL JOURNAL OF MODERN PHYSICS B, 10 NOV. 1997, WORLD SCIENTIFIC, SINGAPORE, vol. 11, no. 28, pages 3311-3317, XP002218401 ISSN: 0217-9792 page 3312, paragraph 1.2 ---	1,3,8,19

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

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"A" document defining the general state of the art which is not considered to be of particular relevance

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"P" document published prior to the international filing date but later than the priority date claimed

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
14 April 2003	23/04/2003

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31–70) 340–2040, Tx. 31 651 epo nl, Fax: (+31–70) 340–3016	Capostagno, E

International Application No
PCT/DK 03/00049

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
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A	JIN WOO JUN ET AL: "Theory of magneto-optical traps for multilevel atoms" LASERS AND ELECTRO-OPTICS, 1999. CLEO/PACIFIC RIM '99. THE PACIFIC RIM CONFERENCE ON SEOUL, SOUTH KOREA 30 AUG.-3 SEPT. 1999, PISCATAWAY, NJ, USA,IEEE, US, 30 August 1999 (1999-08-30), pages 1261-1262, XP010364386 ISBN: 0-7803-5661-6 the whole document	1,2
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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
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A	EP 0 517 454 A (JAPAN RES DEV CORP) 9 December 1992 (1992-12-09) the whole document -----	1

INTERNATIONAL SEARCH REPORT

nformation on patent family members

In tional Application No
PCT/DK 03/00049

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